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Analysis of the Thermal Comfort and Energy Performance of a Thermal Chair for Open Plan Office

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ABSTRACT

The aim of this work is to analyse the thermal comfort and energy performance of a thermal heating chair for open plan office using field experiments, thermal comfort survey and energy simulations. A comprehensive review on the development of thermal chairs was carried out to highlight the present research gaps. The study developed a thermal chair prototype with controllable heating pads, incorporated into the back of the seat and back rest fabric. The field test was carried out in an office building in the UK during the winter. The study showed that the users set the thermal chair temperature between 29-45 °C. The field survey results of the thermal satisfaction survey showed that 19 out of 44 participants felt satisfied before using the device. While after using the thermal chair, the number of satisfied respondents increased to 34. The work also utilised Building Energy Simulation to further assess the thermal comfort and energy performance of the thermal chair. Three cases were simulated: non heated office chair with the zone thermostat maintained at 22 °C, non heated office chair with the zone thermostat at 16-20 °C and thermal chair with the zone thermostat at 16-20 °C.

KEYWORDS

Buildings, Energy simulation, Field testing, Thermal sensation, Thermal comfort.

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INTRODUCTION

Providing a good balance between indoor thermal comfort and Heating, Ventilation and Air-Conditioning (HVAC) energy efficiency is challenging. Reinforced by the growing awareness of the challenges of increasing emissions and the resulting environmental issues, the trend of energy efficient buildings and technologies has been ongoing for decades [1]. It is estimated that up to 50% of energy used in buildings in the UK are used for heating, ventilation and cooling purposes [2]. In order to achieve its goal in reducing carbon emissions from buildings by the year 2050 [3], it is essential to develop technologies and techniques which can significantly minimise the level of energy used for heating and cooling buildings. This is even more challenging due to the increasing levels of thermal comfort requirement of users. According to ASHRAE [4], despite of the significant energy consumption to deliver high level of comfort in the indoor environment, unsatisfactory thermal comfort is one of the most common complaints of occupants. A large percentage of the energy use goes into maintaining a narrow ranges of indoor air temperature that is required for thermal comfort. If the air temperature range or set point can be extended in either the cold or hot direction, significant reduction in energy can be achieved. For example, Hoyt *et al*. [5] estimated that HVAC energy can be reduced by up to 10% per °C set point adjustment.

Technologies such as Personal Comfort System (PCS) allows occupants to have a more comfortable working environment and at the same time reduce energy consumption in buildings. The system directly heats or cools body parts of occupants while relaxing the temperature range in either cold or hot direction. PCS such as thermal chairs, personal ventilator, cool chair can be locally controlled by occupants so as to provide great amount of energy savings since only little amount of energy is used by the system [6], and achieve thermal comfort and the control stability of the HVAC system [7]. Zhang *et al*. [8] produced a review of different types of PCS and found that PCS can save over 30% of a building's total HVAC energy and up to 100% satisfaction of indoor environment by relaxing zone temperature setpoints and reducing HVAC intensity. Hoyt *et al*. [5] evaluated that energy use of efficient PCS is 20-50 times less than that of central heating and cooling systems used by each occupant. In study [9], authors employed the small fans to assist air conditioners in a field experiment in Thailand. The results showed that small fans contributed to save 1,959.51 GWh per year in all air-conditioned space by increasing indoor air temperature setpoint. Vethaart *et al*. [10] analysed the effectiveness and energy usage of personal heating, with its corresponding impact towards the whole building energy load. Through a model assessment technique applied, it acknowledged that personal heating can bring potential towards energy saving of up to 34% for HVAC energy consumption during winter months, while also giving improvements of the individually perceived thermal comfort. Additionally, using personalised control system, energy use per individuals can be decreased and system response time and comfort perception can be improved [11]. The changes in local air velocity and temperature can greatly affect the entire thermal perception of occupants [12]. Wyon [11] revealed that offering personalised control system of ±3 °C near the neutral state can improve the performance of occupants. Energy saving could even be higher if considering the potential of reducing the occurrence of faulty operation of the HVAC such as the simultaneous heating or cooling of the spaces which waste energy and is further increased by the narrow setpoints of air temperature. Luo *et al*. [13] suggests the importance of indoor thermal exposures can strongly influence occupant's thermal adaptation. Through a literature survey by Frontczak and Wargocki [14], it also highlights the effects of indoor building environment towards human comfort, along with Moezzi [15], it evidently illustrates people are not as thermally comfortable in their places of work as to design values and as theory assumes. Hence, this highlights the need of solutions such as personal comfort systems [16] to improve occupants' thermal comfort to

increase productivity and to also reduce illness symptoms of occupants [17]. Additionally, in the study by Habchi *et al*. [18], it revealed personal ventilators can also provide good indoor air quality by reducing cross-contamination between occupants.

Conditioning only the occupants' personal area can certainly provide a more comfortable environmental conditions compared to having an air conditioning system which is accessible to all individuals sitting in the same room [19]. Besides, it is smaller than the room's total capacity, it can reduce energy consumption and at the same time while providing an individual thermal preference [20]. It has been revealed in Cao *et al*. [21] that occupiers who are in control of their own heating requirements have warmer feeling and less neutral temperature at the same indoor temperature compared to individuals working in a district heating environment. The study [21] compared the thermal comfort in building supplied by district heating (hot water is supplied via pipelines to each terminal from a central heating station) and individual heating (hot water was produced by a wall-mounted gas boiler in each unit). Just being aware of having control options can support psychological adaptation [22] and influence the satisfaction level of occupants.

The extensive differences in individual physiology is also one of the important issues in personalised thermal comfort measures. Mean skin temperature, tympanic, and other body organs can differ by around 5, 0.8, 2, and 1 °C, individually [23]. According to Takada *et al*. [24] and Havenith and Van Middendorp [25], the important individual factors are body surface area to body mass ratio, fat mass, sweat rates, maxVO2 use and heart rate. Conversely, personalised evaluations such as local warming showed to have a definite impact on providing better comfort, throughout gender and age groups [26]. Studies [27] on human behaviour have demonstrated that elder individuals can encounter difficulties in keeping up with steady core temperature which means that aged body cannot avoid heat loss when experienced cold condition. There has also been an ongoing debate on load error for positive thermic perception, where it is believed that it is merely caused by changes in the whole-body temperature [28]. Latest researches demonstrate that few differences in localised thermal stimuli and skin temperature can create enough load error for positive alliesthesia sensation [29], whereas the body, overall still depends on thermoneutral area.

In this study, the thermal comfort of occupants using a non heated and thermal chair will be analysed and evaluated. The investigation will be conducted in an office plan where a thermal chair prototype was provided to occupants. The energy and thermal performance of the thermal chair will be examined using Building Energy Simulation (BES). A three-storey office building with standard and thermal chairs will be generated and simulated in the BES tool Integrated Environmental Solutions (IES VE), validated with data from the literature. Three cases will be simulated, non heated office chair with the zone thermostat maintained at 22 °C, non heated office chair with the zone thermostat at 16-20 °C and thermal chair with the zone thermostat at 16-20 °C.

DEVELOPMENT OF THERMAL CHAIR

This section will review the available researches on personalised comfort systems in particular thermal chairs for offices. Different designs of thermal chair will be examined to provide a comprehensive analysis on which design can provide the best optimal performance in terms of comfort and energy consumption. Niu *et al*. [30] presented a thermal chair with personalised ventilation and air supply directed towards the breathing region that supplies fresh air with controlling settings of air temperature, as shown in Figure 1. The ventilation performance of the thermal chair was investigated using a manikin seated on the chair. Certain measurements and 8 types of air terminal devices were investigated to examine the efficiency of providing fresh air supply. The results have demonstrated that occupiers were not comfortable with the personalised airflow as compared with personalised air temperature. The experiment carried out for air terminal devices found up to 80% reduction in the level of pollutants in the inhaled air when the air

supply rate was < 3.0 L/s. But this does not mean that the entire inhaled air contains personalised fresh air supply even when the nozzle was positioned directly at the nose of the occupants.

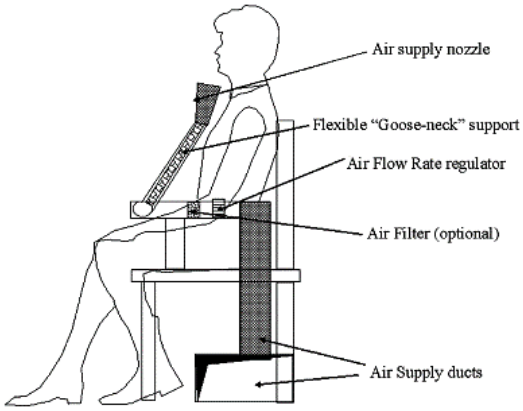

Figure 1. Personalised ventilated personal comfort system [30]

Figure 2 presents the type of chair used within Pasut *et al*. [31] study. This designed heated/cooled chair was used for the obtainment of comfortable conditions for up to 90% of the individuals at a range of 18 °C to 29 °C ambient temperature, whereas 75% were comfortable at 16 °C. The results showed that the energy savings is not offset by the consumed energy of the thermal chair as it was low compared to the central heating system. Additionally, in Pasut *et al*. [32] study, a cooled/heated chair with thermoelectric device was investigated. It provided an increase or decrease temperature throughout the seat and back rest region. Experiments were carried out in a climate chamber with temperature of 16, 18, 25, and 29 °C. Occupants can fully regulate the temperature surrounding the chair, which was positioned on the desk. The result revealed that this type of chair can provide a significant effect on occupiers' thermal comfort in both cool and warm settings. While in the case of energy saving, it has revealed that the typical consumed power was around 27 W for 16 °C, whereas for 29 °C climate chamber temperature, it used 45.5 W. However, the study concluded that this type of comfort system cannot replace the HVAC devices because of its high cost.

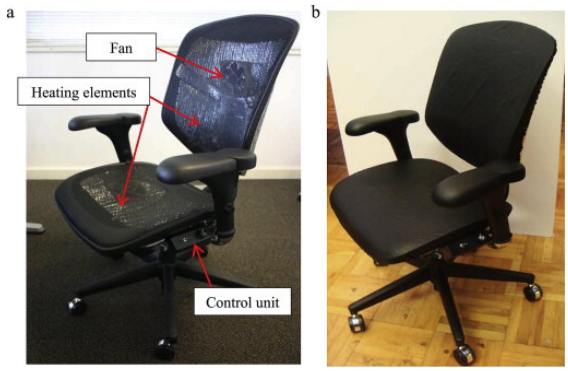

Figure 2. APCS device (a) and heating elements and fan installed on mesh thermal chair (b) covered thermal chair [32]

Researchers from UC Berkely developed a cooling and heating office chair called the Hyperchair, which allow occupiers to regulate their preferred temperature only within their personal space [33]. The chair was installed with heating tape knitted into the fabric of the chair and incorporated with fans to heat up the occupiers and the temperature can be controlled using smartphone application or a button that can be pushed on the side.

Furthermore, the chairs were incorporated with temperature sensors and WiFi which allows to communicate with the building management system. It was highlighted that the chair can provide 5-10% of energy savings. However, each unit is very costly (USD 1,000-1,500 per unit).

Hecheng *et al*. [34] studied the performance of a heated seat and back rest cushions in a climate chamber with 14, 16 and 18 °C ambient temperature. Results indicated that the added active heating did not have any great advantage for the entire thermal comfort assessment with temperature of 16 °C and 18 °C and only showed limited potential of thermal sensation at 14 °C. Because of heat produced by human body, the buttocks and back of individuals that are in direct contact with the thermal chair will not feel cold if the chair's thermal insulation is adequate. Moreover, the heated chairs did not enhance the performance of thermal sensation around the extremities which limits the effect of chair heating. Thus, heating devices must not be installed around the extremities. In the case of thermal chair, enough insulation may reach the similar effect on thermal comfort with active heating in ambient condition not less than 16 °C. While in Zhao *et al*. [35] research, combination of seat and back fans with heating pads installed at the seat and back of the chair for the application in both warm and cold weather condition.

On the other hand, several researchers focused on providing cooling using the office chair. For car businesses, warm or cooled chair were usually applied [36] while in few researches, water tubes were applied for heating and cooling purposes [37]. In Tsuzuki *et al*. [38] study, it was revealed that the heating pads applied on the chair is more effective compared to cooling. For all of these studies, experiments were mostly carried out in climate chambers than the real-world setting, which can provide valuable information that affects the level of thermal comfort for occupants [39]. However, results of the experiments carried out in chamber may not apply to the real-world setting [40].

Watanabe *et al*. [41] carried out a subjective study during summer to evaluate the chair's performance installed with 2 fans that can offer isothermal forced air flow to the occupiers. The experiments were conducted on summer with 26, 28, 30 and 32 °C room air temperature and 7 male students were allowed to regulate the 2 built in fans by controlling dials on the desk. Findings showed that 28 °C and 30 °C air temperature were satisfactory based on the occupiers' evaluation. College students have addressed that a thermally comfortable and neutral regardless of which type of chair used with 28 °C air temperature. Whereas for room set at 30 °C air temperature, occupants reported that it offered an acceptable thermal environment concerning comfort, chair installed with fans and full body thermal sensation and demonstrated great reduction in discomfort level at the lower back and back where isothermal air flows were directed to. But room temperature with 32 °C were not effective in offering an acceptable thermal environment for occupiers.

Sun *et al*. [42] assessed a new design of thermal chair with 4 fans installed under the areas of the chair seat. This allows the cool air close to the floor level and increases the convection airflow all over the body parts. Tests were conducted in Singapore in a regulated climate chamber with displacement ventilation and similar rate of heat load at dissimilar supply of temperatures such as 20, 22, 24 and 22, 24, 26 °C room air temperature. 32 students including 16 females and males were involved in the experiments. Participants were doing their typical work throughout the time of experiment in the climate chamber. Results of the study demonstrated that occupiers who chose high level of air distribution and were satisfied with the cooling produced by the fans in of 26 °C ambient temperature. However, the occupiers who experienced cooler all throughout the waist at 22 and 24 °C air temperature during the fans were used. Therefore, air distribution around the occupants can assist in balancing the warm thermal feeling at high ambient air temperature. Kogowa *et al*. [40] designed a cool chair which is installed with isothermal air flow generator and allow individuals to regulate the local thermal

temperature through altering air flow velocity with the body surface. Results have revealed that this type of chair can offer satisfaction with freedom of control, thermal comfort, and conserve energy. Figure 3 presents the airflow diagram of the cool chair, where air is drawn into the seat and the backrest and is then blown out through the armrests.

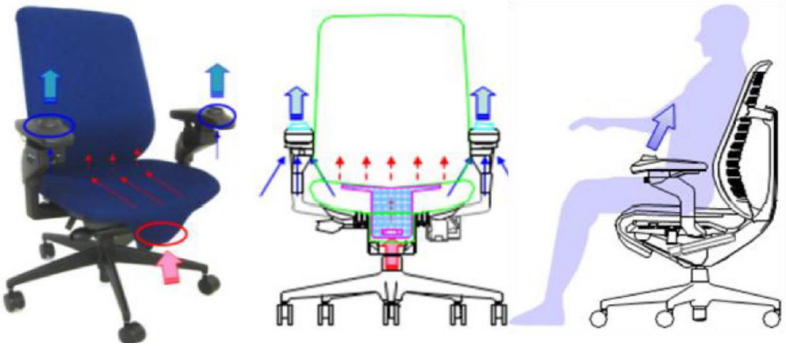

Figure 3. Airflow though the arm rest and seat of the cool chair [43]

Onga *et al*. [44] also investigated the performance of cool chair in terms of thermal comfort. The study used adopting model such as physiological, psychological, and behavioural adjustments. Examination was conducted in a climatic chamber during summer in Kogakuin University. The clothing thermal resistance of male clothes was at 0.64 clo, whereas 0.65 clo for female clothes. There were total of 37 participants involved in the experiment, 18 male and 19 female college students. Results found that that female subjects frequently changes the airflow level than males. Female subjects have reported that is due to their worn clothes. Also, it was also observed that participants felt comfortable with personal control systems and reported a facial dryness, however, did not progress as the coming airflow have already resolved the issue.

It was observed that only a few studies focused on how the temperature of seats affects occupants' activities and also the kind of material used which can affect the thermal comfort of user. Different kinds of chairs were investigated in using temperature sensor device and visualised infrared thermography to determine whether such materials and types of seats can influence the performance of thermal chair. The study of Liu *et al*. [45] compared thermal performance of 3 chair configurations through temperature sensor device, which can monitor temperature differences on the overall body seat interface in actual setting. Moreover, it is proved that the temperature field at the area of interaction is not consistently distributed and this is the only research to empirically showed the distribution without disrupting the sitting arrangement. Results of the study also showed that the material used can clearly influence the retention and distribution of heat around the chair surface material. Lastly, this type of sensor devices can carry out several interferences to be tested in a more realistic condition, without interfering the occupant's activity while sitting.

Sales *et al*. [46] measured the temperature level of eight different kinds of chairs made from different materials. The materials of the furniture in contact with the occupants and thermal response of the material to cooling and heating were measured. With the aid of infrared thermography, results showed that all types of seats have demonstrated high cooling level in the 1st 5-minute testing and gradually lowered cooling rate after 10 minutes, this may be due to the level of room temperature.

As observed in the literature review, there are already many studies on personal comfort systems and thermal chairs using laboratory or controlled experiments. However, the analysis of such systems in the field, in particular, in open plan offices is limited. Furthermore, there are limited studies on the analysis of the energy performance of

offices/buildings with thermal chairs. A recent study by Veselý *et al*. [47] numerically investigated the energy performance of a personalised heating systems in a medium sized office in relation to the building fabric characteristics and climatic conditions. The study used a combination of two tools to carry out the numerical analysis: Energyplus to simulate the building energy consumption and Predicted Mean Vote (PMV) and Matlab to predict the energy saving potential of the personalised heating systems. The Matlab model uses data from an earlier experimental study [48] carried out in a climatic chamber, which provides the relationships between thermal sensation gains and the corresponding energy use. The results showed up to 73 kWh/m^{2}y energy saving can be achieved by reducing the setpoint from 21 °C to 18 °C. The present work will address the gaps in the literature by carrying out field experiments and Building Energy Simulations. The field experiment will be carried out in an actual office environment which will focus on how the users adjust the thermal chair temperature settings, the thermal preference and satisfaction before and after using the device. Unlike previous works, the thermal chair units will be integrated into the multi zone building energy simulation model to predict the energy consumption of the building with and without the device. The approach allows the investigation of the temperature and comfort level in various locations, for example, how would a thermal chair perform in the middle of the room as compared to a thermal chair near the window. Furthermore, the present study will also investigate the effect of adjusting the set point from 22 to 20 °C, 18 and 16 °C.

RESEARCH METHOD

In this study, a prototype of a thermal chair was developed by modifying a typical office chair. Two heating pads each with 30 W heat output were incorporated into the back of the seat and back rest fabric. The foam of the seat and back rest provided insulation and ensured that most of the heat is directed towards the user. Figure 4 shows the thermal images of the areas of the chair that are heated. The study used a FLIR T660 Infrared Thermal Imaging Camera with a measuring range of –40 °C to +150 °C and accuracy of ±2 °C (±3.6 °F) or 2%, whichever is greater, at 25 °C. The heating pads were connected to two modified temperature thermostats as shown in Figure 5. The dial which was calibrated in Celsius provided an accessible controller for the seated user, located at each arm rest for easy adjustment. This also allowed for the set temperatures to be monitored and logged during the field study. Figure 6 shows the typical temperature at various thermostat settings and the equivalent average energy consumption, measured by a thermocouple and data logger and energy meter. The surface temperature is recorded using a Type-K thermocouple and TC-08 thermocouple data logger with a measuring range of −270 to 1, 370 °C, accuracy of ±0.5 °C and resolution of 0.025 °C. The temperature data is also used to verify the thermal imaging results. The energy consumption is recorded using a Current Cost energy meter and appliance monitor with an accuracy of 3%.

This study aimed to investigate the subject in the context of everyday life comparing thermal preference and satisfaction before and after using the thermal chair. The field test was carried out in a modern four storey open plan office building in Leeds, UK. Leeds is a city in West Yorkshire, located at latitude 53.8 and longitude 1.54, classified as warm and temperate climate. The mean outdoor air temperature is 15 °C in July and 14 °C in January. The relative humidity is around 79% in summer and 90% in winter. The dry bulb temperature and relative humidity are measured using a PCE-GA 70 m with a measuring range of 5 to 50 °C/10 to 90% RH, accuracy of ±0.5 °C/±3 RH and resolution of 0.1 °C/0.1% RH. The temperature data is also used to verify the thermal imaging results. The investigation was conducted during the month of December. The building incorporates passive solar glazing, heavy mass, heat recovery air handling units and demand driven ventilation system.

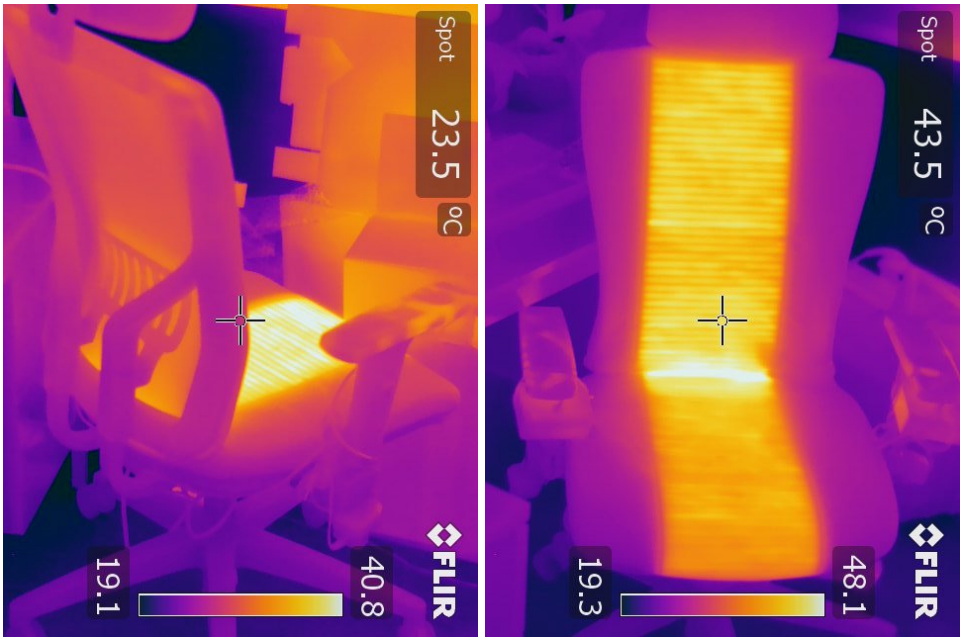

Figure 4. Thermal images of the heated surfaces of the thermal chair

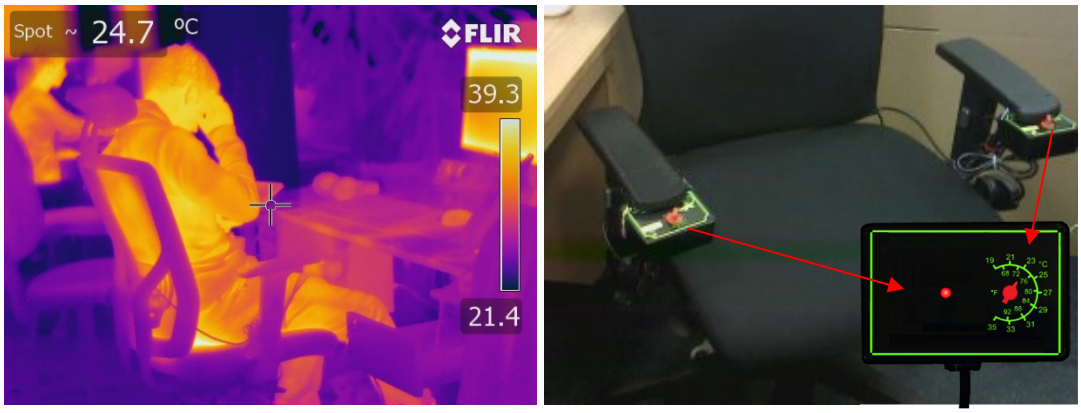

Figure 5. Thermal image of the thermal chair during the field test (a) and on board controls for seat and backrest heating (b)

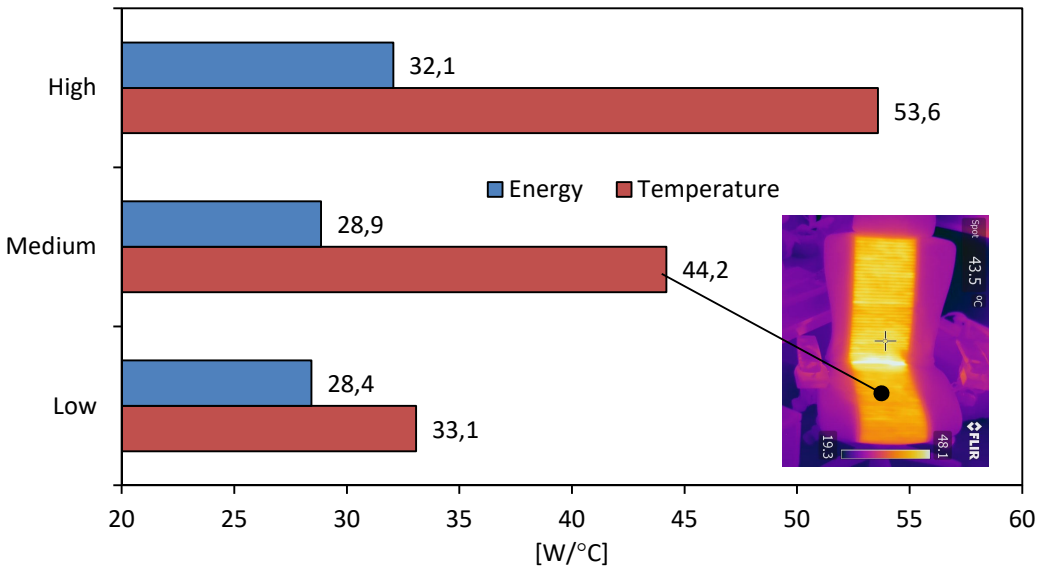

Figure 6. Energy consumption of the thermal chair and surface temperature at various settings

During the test, the average indoor air temperature was 24 °C and the average of the indoor relative humidity was 29%. There were 44 participants with 15 females and 29 males, who are mostly PhD students and researchers. Each participant was sat on the thermal chair during the test period and were asked to go about their typical work. The duration of each test was 1 hour. The tests occurred during the normal working hours (10:00 to 17:00). The participants were mostly wearing typical indoor winter clothing. The activities in the open plan office were mainly sedentary activities. Their views of comfort and satisfaction were recorded before and after the use of the thermal chair via a survey questionnaire based on the ASHRAE seven-point thermal sensation and satisfaction scale as shown in Table 1. A portable device (iPad) was used for the mobile survey which allowed instant feedback to the multiple-choice questionnaire.

Table 1. Survey questions based on the ASHRAE seven-point scale [4, 17, 49, 50, 51, 52]

Currently, I prefer to overall feel:							
Much warmer	Warmer	Slightly warmer	No change	Slightly cooler	Cooler	Much cooler	No strong opinion
3	2	1	0	−1	−2	−3	
Satisfaction with the thermal chair:							
Very satisfied	Satisfied	Slightly satisfied	Neutral	Slightly dissatisfied	Dissatisfied	Very dissatisfied	No strong opinion
3	2	1	0	−1	−2	−3	

This research will use the BES tool IESVE to assess the energy performance of the office building with thermal chair.

The BES is based on the commercial tool IESVE which is a dynamic thermal simulation based on the modelling of the heat transfer processes between a building and its microclimate. Within the tool the conduction, convection and radiation heat transfer processes for each building component or fabric are modelled individually and incorporated with the model of the heat gains, air exchange and plant within and around a thermal space or room. The methods and approach used to model these processes are summarised here. The time-dependent spatial temperature distribution in a solid without internal heat sources is given by the partial differential equations:

$$W = -\lambda \nabla T \tag{1}$$

$$\nabla \times W = -\rho c_p \frac{\partial T}{\partial t} \tag{2}$$

where T is the temperature, W is the heat flux vector, λ is the conductivity, ρ is the density and c_p is the specific heat capacity. The heat storage in air masses or net heat flow into the air masses Q is modelled by the following equation:

$$Q = c_p \rho_a V \frac{\partial T_a}{\partial t} \tag{3}$$

where V is the air volume, ρ_a is the air density and T_a is the air temperature.

For the discretisation, the tool uses a finite difference approach to the heat diffusion equation solution which first replaces the element with a finite number of discrete nodes at which the temperature will be calculated. The nodes are distributed within the layers for the modelling of the heat transfer and storage characteristics for the selected time step. This choice is based on constraints imposed on the Fourier number. Then, the time variable is discretised and a combination between explicit and implicit time-stepping scheme is adopted in order to alternate nodes of the construction. The convective heat transfer is described by the equation:

$$W_{\mathrm{hf}} = K(T_{\mathrm{a}} - T_{\mathrm{s}})^n \tag{4}$$

where W_{hf} is the heat flux from the air to the surface, T_{s} is the mean surface temperature and K and n are coefficients.

The heat transfer rate associated with an air stream entering a space is described by equation:

$$Q = Mc_p(T_{\mathrm{i}} - T_{\mathrm{a}}) \tag{5}$$

where M is the air mass flow rate, T_{i} is the supply air temperature and T_{a} is the room mean air temperature.

For the interior long-wave radiation, the net radiant exchange between a surface and the rest of the enclosure is described by the equation:

$$W_{\mathrm{rl}} = h_{\mathrm{r}}(T_{\mathrm{s}} - T_{\mathrm{MRT}}) \tag{6}$$

where W_{rl} is the net radiative loss from the surface, h_{r} is the surface heat transfer coefficient for exchange with the MRT node and T_{MRT} is the mean radiant temperature.

For the exterior long-wave radiation, the net long-wave gain for an external surface of inclination β [°] is represented by the following equation:

$$L^*(\beta) = \varepsilon_{\mathrm{e}}[L_{\mathrm{Skv}}(\beta) + L_9(\beta) - \sigma\Theta_{\mathrm{e}}^1] \tag{7}$$

where ε_{e} is the emissivity of the exterior surface, $L_{\mathrm{Skv}}(\beta)$ is the long-wave radiation received directly from the sky, $L_9(\beta)$ is the long-wave radiation received from the ground and Θ_{e} is the absolute temperature of the exterior surface. The tool calculates the solar flux incident on every external building surface at each time-step.

A building in London with a 1,536 m^2 floor area with a height of 10.5 m [53] is modelled in the present study. Similar to the building in the experimental work, the building is also a narrow open plan office type. It was decided to create the BES model based on previous work due to the availability of energy data which is necessary for validation. As shown in Figure 7, the building has 3 floors and each floor has a height of 3.5 m and similar layout. For simplification, some features of the buildings and surroundings were not modelled such as the window recess. Each floor was split into two areas, large open plan office area and common areas. The areas were represented as thermal zones in BES to set different operation profiles. The construction properties were set according to UK standards, Approved Document L2A. The U-value of the wall, roof, ground and glazing were 0.25, 0.15, 0.15 and 1.78 W/m^{2}K. The window solar heat gain coefficient was 0.64 while the visible transmittance was 0.76 [53]. For the modelling of the thermal chair, 40 equally spaced units were incorporated to each floor of the building model as shown in Figure 8.

The London/Gatwick weather data file was used for the simulations. The building was assumed to be in use during weekdays from 7:00 to 19:00 and close during weekend. The indoor conditions were strictly controlled in these periods. The office thermal zone was maintained at 22 °C during heating period and at 24 °C during cooling period and the common area thermal zone was heated up to 20 °C and cooled to 26 °C. Overheating is prevented in the office during unoccupied times by cooling the space when indoor temperature reaches 28 °C in the office and 30 °C in common area. While, the heating is turned on if temperature drops below 12 °C for both zones [53].

To simulate the internal gains in the office, profiles for lighting, occupancy and equipment were set and assumed to follow the building heating/cooling operation profile. The lighting max sensible gain was set to 12 W/m^2. The occupancy density was set to 9 m^2/person with a sensible and latent heat gain of 80 and 45 W/person. The equipment

was assumed to be computers and set to 15 W/m^2. For the air exchanges, the mechanical ventilation max flow was set to 10 L/s/person and infiltration rate value was set to 0.3 ach [53]. In order to simplify the simulations, it will be assumed that the thermal chair will operate from 7:00 to 19:00 during weekdays. Similar to the developed prototype the thermal chair seat and back rest were heated and initially set to 30 W.

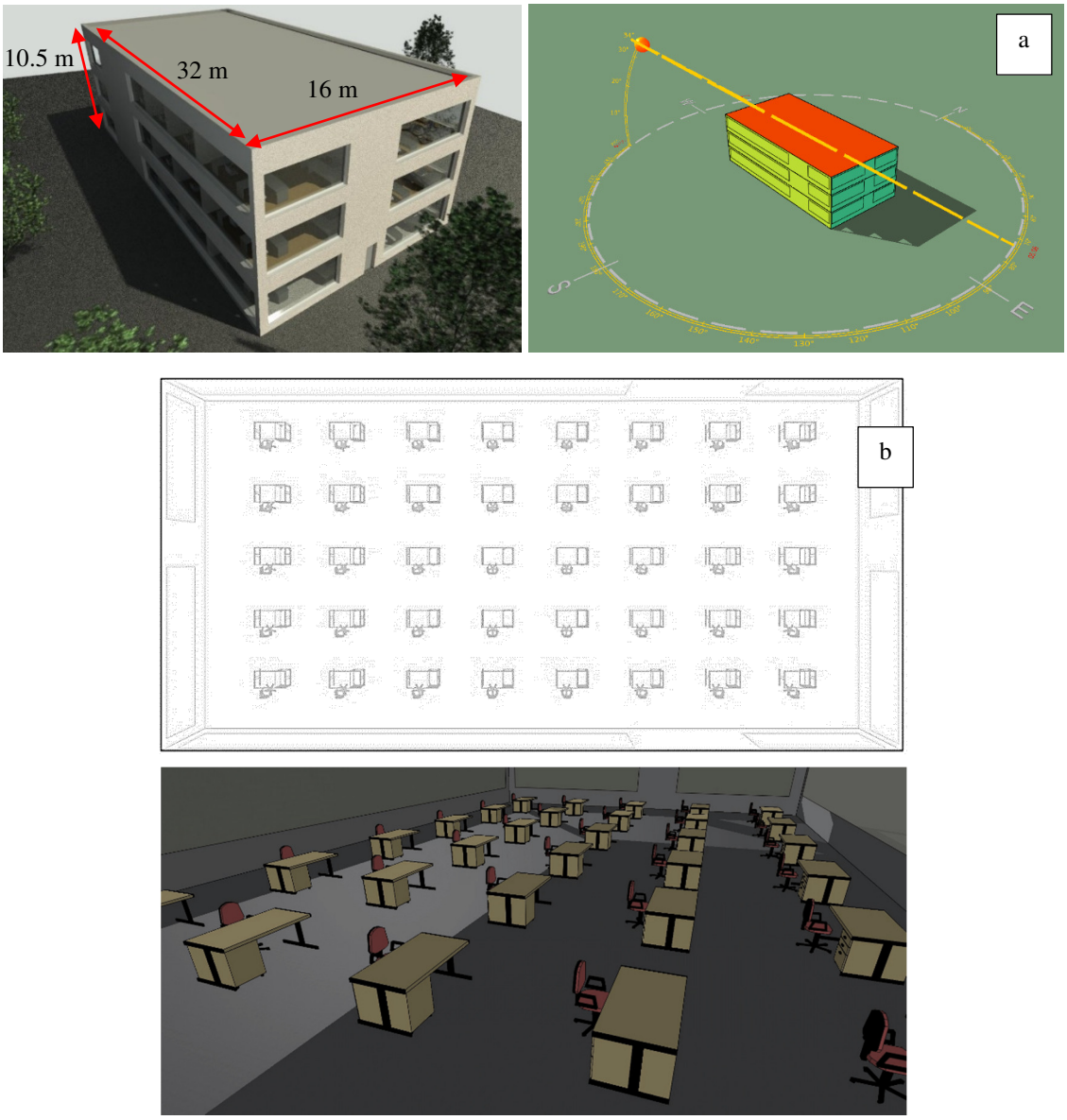

Figure 7. 3D model of the open plan office building model based on the study of [53] (a) and arrangement of thermal chair in the open plan office building model (b)

RESULTS AND DISCUSSIONS

During the experiment, the users of the thermal chair were advised to adjust the settings of the thermal chair temperature for the seat and the back rest according to their preference. Figure 8 shows the set temperature for the seat and backrest during the field survey of the thermal chair. As observed, the set temperature ranged between 29-45 °C while several did not use the backrest heating (3 users), seat heating (2 users) or both (1 user). It should be noted that the user who did not turn on both the heating devices felt slightly warm (seat and back rest area) when using the non heated chair and was satisfied with the thermal environment (air temperature was at 25.5 °C and humidity at 29.7%). While the users that did not turn on the seat or backrest heating felt slightly warm near the

seat or backrest area when using the non heated chair. Only 3 users set the temperature above 42 °C, however, the users did not exactly feel Cold/Cool/Slight Cold while using the non heated chair and after using the chair they felt Warm-Hot but was Satisfied or Slightly Satisfied after using the thermal chair. The field study survey also highlighted that majority of the users preferred separate controls for the seat or backrest heating.

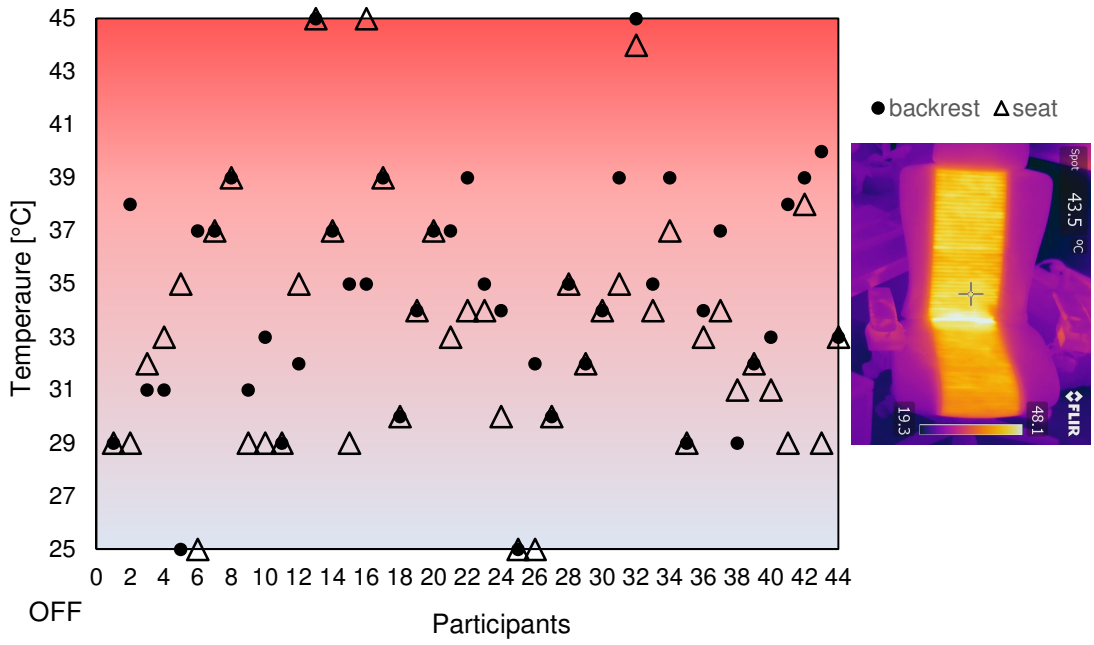

Figure 8. Temperature set by the participants for the seat and backrest during the field survey of the thermal chair

In the field survey study of thermal comfort, users' thermal preference were compared before and after using the device. As observed on Figure 9, 22 out of 44 respondents preferred the thermal environment to be much Warmer/Warmer/Slightly Warmer before using the chair and reduced to 17 after using the thermal chair. Only 3 users preferred a Much Warmer environment after using the thermal chair, however, they already felt Warm-Hot while using the thermal chair and felt Satisfied/Very Satisfied with the thermal environment. It should be noted that all 3 had their heating for back rest/seat set below 37 °C. This is the same case with the 4 users who preferred a Warmer environment after using the thermal chair, they already felt Slightly Warm/Warm while using the device. Among the 10 users who preferred a Slightly Warmer environment, after using the thermal chair, only 1 user felt Slightly Cooler while using the device while most felt Slightly Warmer/no change. Overall, 19 out of 44 respondents preferred no change after using the thermal chair and their thermal sensation varied from Neutral to Hot. While before using the thermal chair, 8 out of 14 who responded No change already felt Neutral. 4 participants preferred a Cooler environment and their thermal sensation varied from Cool to Hot. It should be noted that the participants had their heating for backrest/seat set between 29-35 °C with 2 of them setting one of the devices off.

Figure 10 demonstrates satisfaction status of the occupants before and after using the thermal chair. 19 out of 44 participants felt Satisfied/Very Satisfied before using the device. Out of this number, 15 of the respondents felt between Neutral to Warm local thermal sensation. While 4 out those who were Slightly dissatisfied with the overall environment felt between Neutral to Slightly Warm local thermal sensation. After using the thermal chair, the number of Satisfied/Very Satisfied respondents increased by 79%. This agrees with the findings of Shahzad *et al*. [51] which highlighted that the availability of thermal control that allowed individual difference improved user satisfaction. Out of

the 34 Satisfied/Very Satisfied users, 28 felt between Slightly Warm local thermal sensations and Warm with only 2 users feeling Neutral. These suggests that users preferred to feel warmer than neutral for their overall thermal sensation, the thermal sensation on their back and their seat.

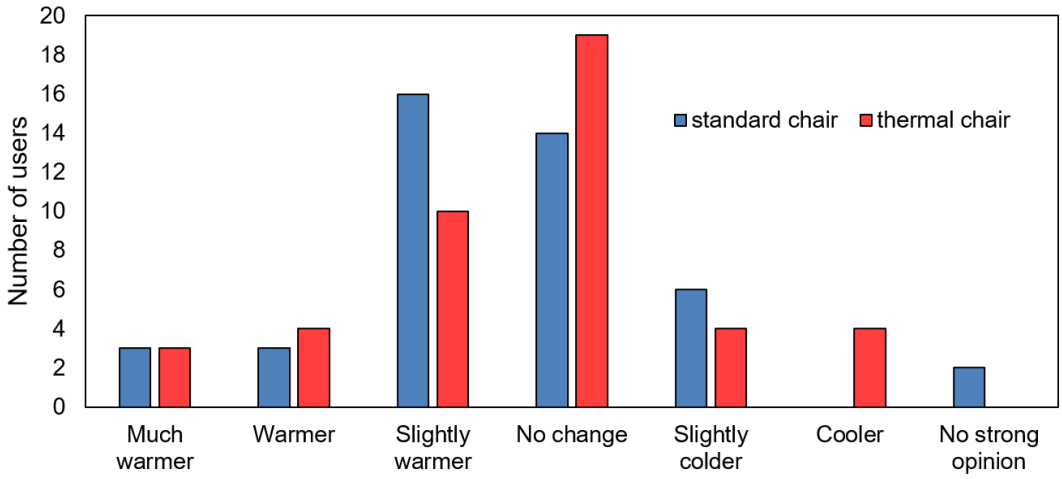

Figure 9. Thermal preference before and after using the chair

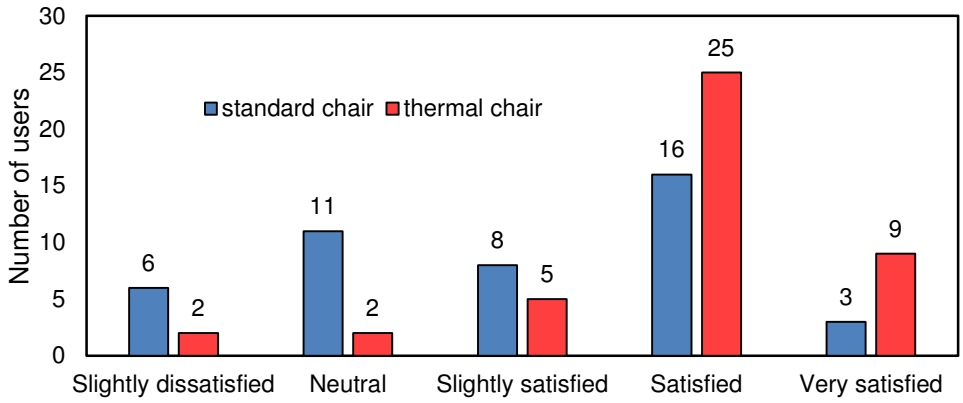

Figure 10. Satisfaction of the participants before and after using the chair

In order to assess the accuracy of the building energy simulation model, validation was carried out by comparing the results with the data of Korolija *et al*. [53]. As observed in Figure 11, a good agreement was observed between the annual simulation results for heating energy demand (9.7% error) and cooling and energy demand (7.8% error). The potential cause of the error is the difference in weather data, cooling/heating systems and the method employed in the studies. Clearly the building can also benefit from a thermal cooling chair which can potentially reduce the high cooling demand, however, the present work will only focus on heating.

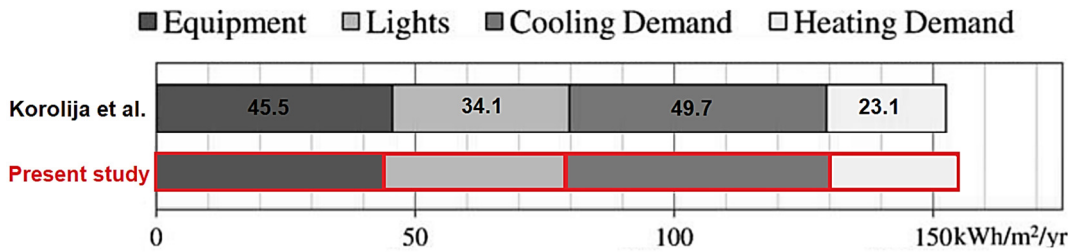

Figure 11. Validation of the simulation results of annual energy consumption with Korolija *et al*. [53]

For the base case, the office space was initially simulated with non heated chairs with the zone thermostat heating set point set at 22 °C during weekdays. As observed in the results in Figure 12 (17th-23rd February), the air temperature around the chair (Chair 1) varied around 21.5 to 22 °C during the occupancy period except for Thursday when it went above 22 °C, due to the high solar gains (up to 7 kW) and the location of Chair 1, which was close to the windows. This highlights the advantage of using an integrated model which allows for the analysis of the thermal chair together with the building, which typically will have a non-uniform indoor environment. Overall, the air temperature patterns followed the set profile with the heating on from 7:00 to 19:00. It can also be observed the time for air temperature to drop because of the stored heat is released from the fabric. The temperature was held at 12 °C when the building was not occupied. As observed, the heating load for the Ground Floor ranged between 14-30 kW during the occupancy period. It should be noted that the outdoor air temperature was lower than 5 °C for a total of 57 hours during the occupancy period from 17th-21st February and hence the high heating demand (1.09 MWh). As observed in Figure 13, the Percentage of People Dissatisfied (PPD) was maintained below 5.8% during occupancy hours. It can also be observed the slight difference in PPD for Chair 1 which was located close to the window and Chair 21 located in the middle of the room.

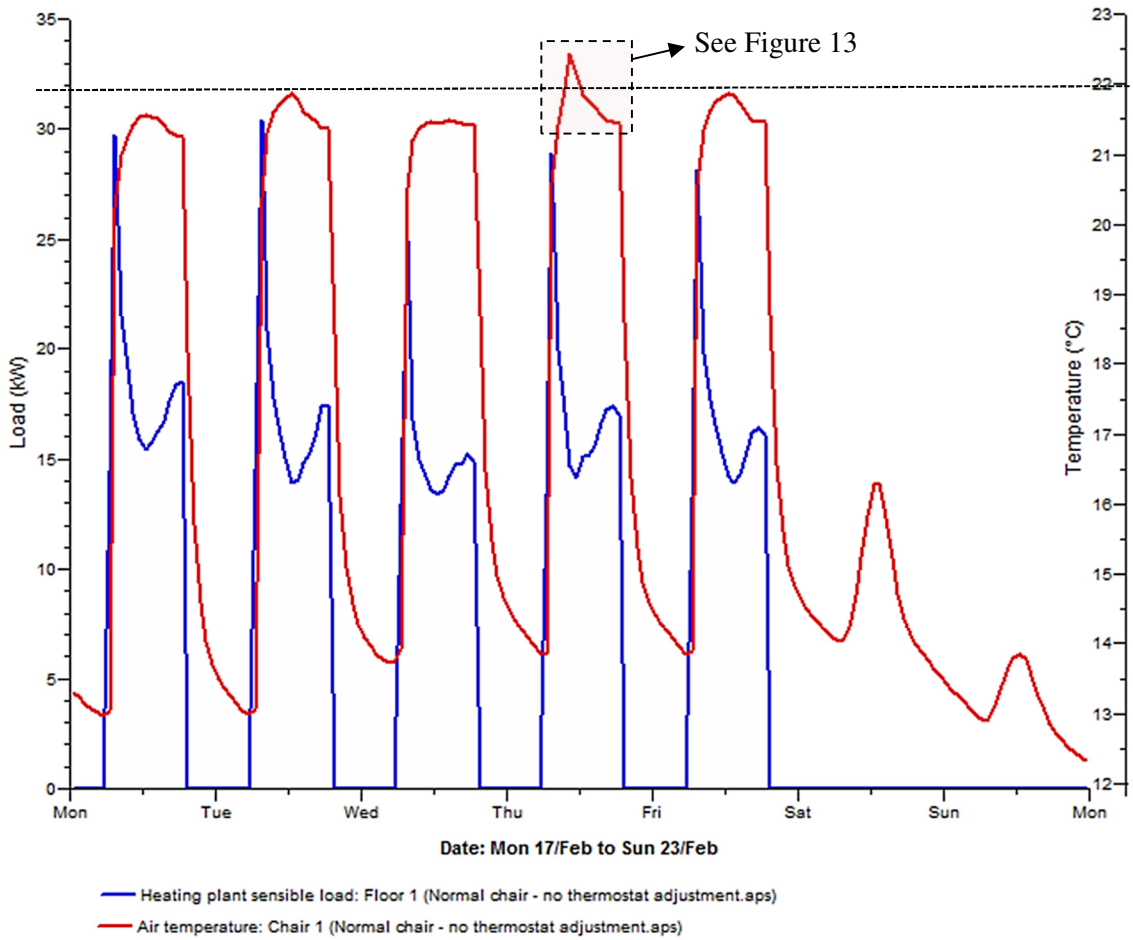

Figure 12. Air temperature results around the non heated chair and predicted heating load (17th-23rd February)

The next case will investigate the effect of lowering the zone thermostat heating set points to 20, 18 and 16 °C on the building energy consumption and thermal comfort around the unheated chair. As seen in Figure 14, similar trend can be observed for the air temperature for all the set points. The air temperature was mostly below the setpoint

value during the occupied hours, i.e. when the set point was at 20 °C, the air temperature ranged between 18.5 to 20 °C except on Thursday when high levels of solar gains was observed. This was observed for all set points except for 16 °C when the air temperature ranged between 15.5 to 17 °C. Clearly reducing during the heating period, lowering the set point by a degree few degrees can reduce the energy demand, however, this could also lead to discomfort to occupants as shown in Figure 15 which presents the results of PPD. Without any additional heating from the thermal chair, the PMV value decreased from 0 (neutral) to −1.4 (slightly cold) as the set point was decreased from 22 to 16 °C. It should be noted that the PMV values were predicated based on the following assumptions: clothing level (0.70), activity level (sedentary activity) and air speed of 0.15 m/s.

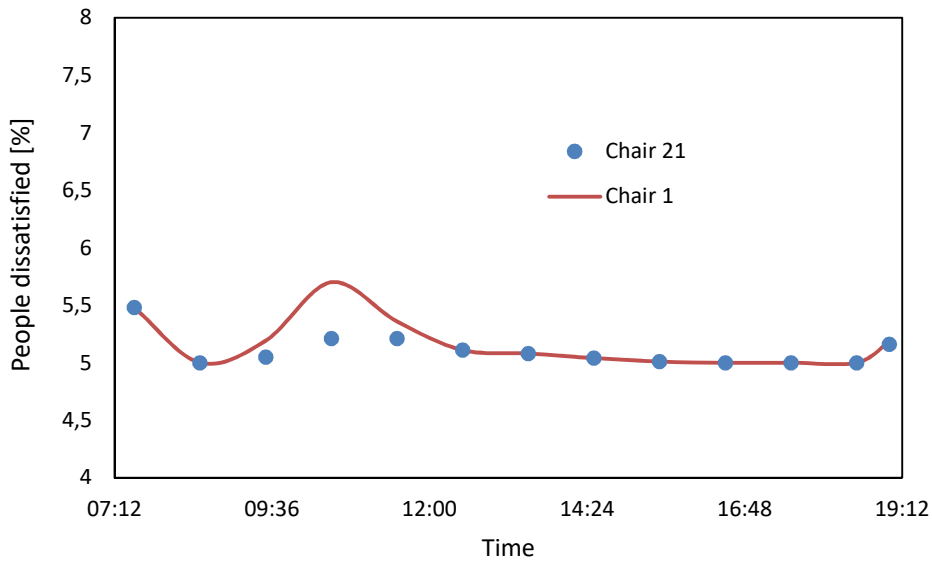

Figure 13. PPD during occupancy time (February 20th)

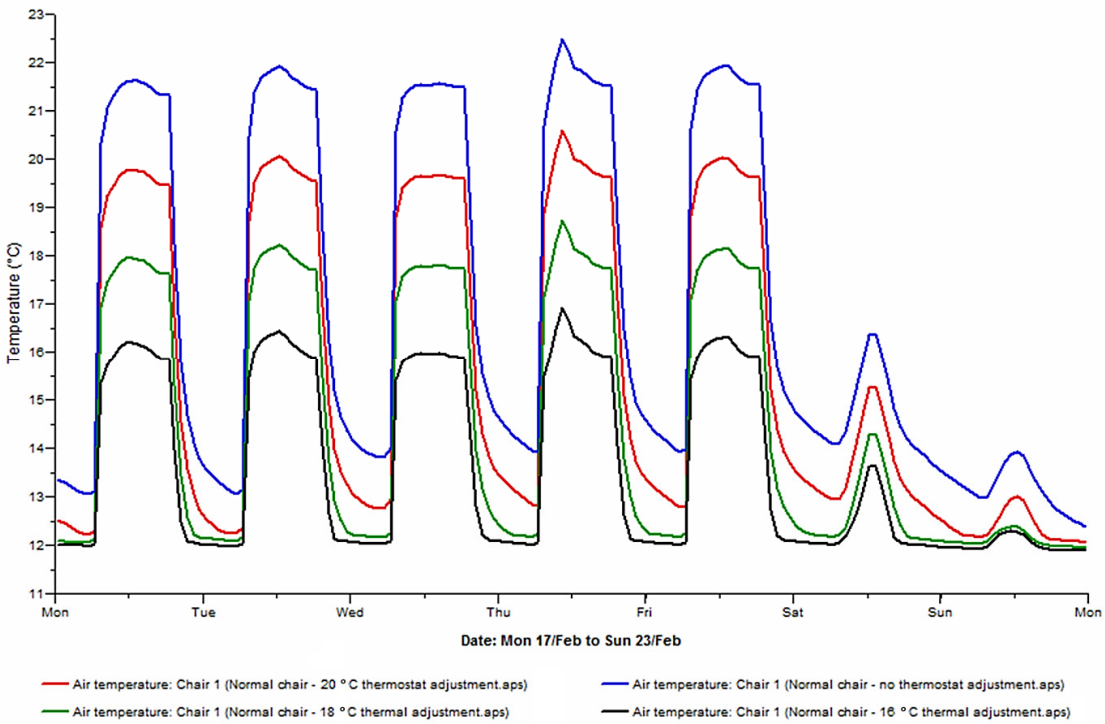

Figure 14. Air temperature results around the non heated chair when the setpoint was adjusted to 20, 18 and 16 °C (17th-23rd February)

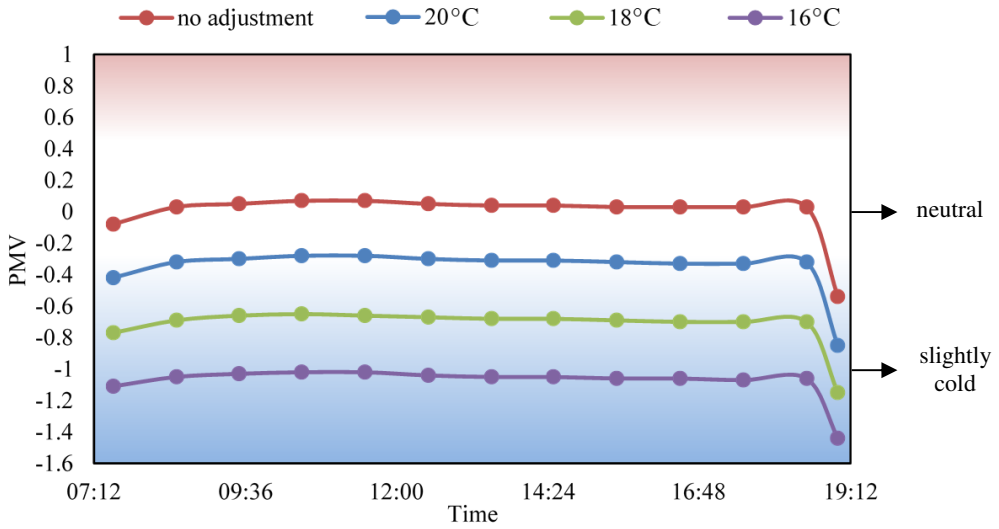

Figure 15. PMV around the non heated chair when the setpoint was adjusted to 20, 18 and 16 °C (February 20th)

The next case will investigate the potential of thermal chair to reduce building energy consumption and at the same time provide local comfort to the occupants while extending the zone thermostat heating set points to 20, 18 and 16 °C. Although the thermal chair can be adjusted by the occupants to the desired temperature levels, in the simulations the heat output of the chair (30 W) was fixed and was on from 7:00 to 19:00, follow that of the occupancy schedule. Figure 16 compares the predicted results of the air temperature around Chair 1 for the thermal chair with various thermostat adjustments and non-heated chair (base case). As observed, the air temperature was mostly above the setpoint value during the occupied hours, i.e. when the set point was at 20 °C, the air temperature ranged between 20.5 to 22 °C. As observed in Figure 17, the thermal chair was able to maintain the PPD below 16% during the occupancy hours for set point 18 °C and higher. On average the PPD was reduced by 5.6% due to the additional heating from the thermal chair when the set point was at 18 °C and 8.7% at 16 °C.

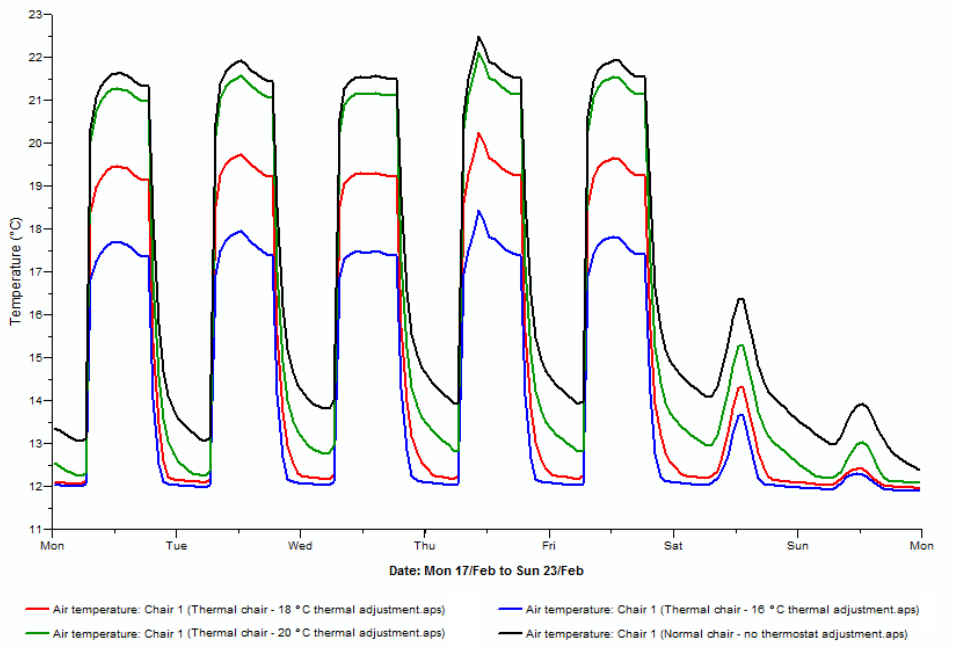

Figure 16. Air temperature results around the heated chair when the setpoint was adjusted to 20, 18 and 16 °C (17th-23rd February)

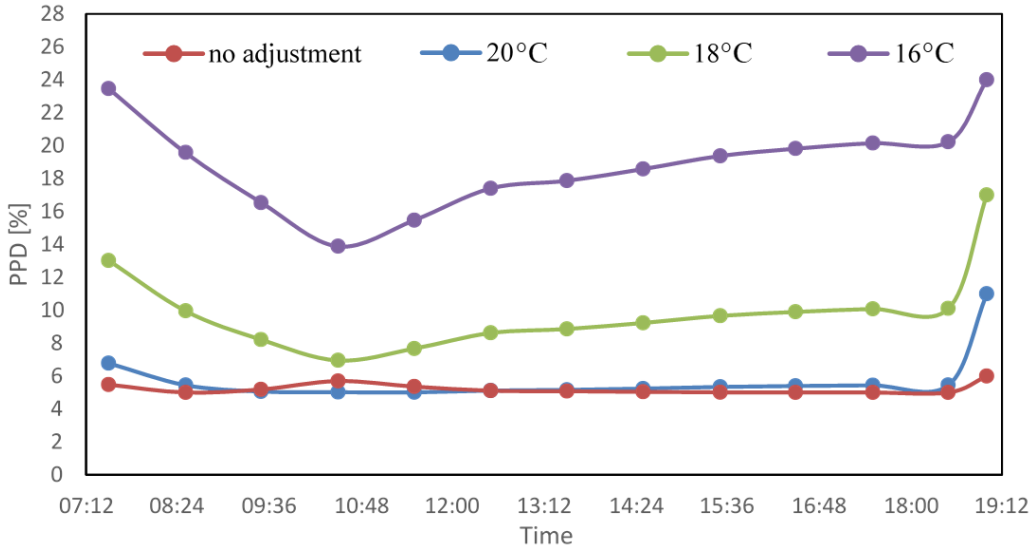

Figure 17. PPD around the heated chair when the setpoint was adjusted to 20, 18 and 16 °C (February 20th)

Figure 18 compares the weekly heating energy demand for the open plan office (Ground Floor) with thermal chair with thermostat adjustment and non-heated chair. As observed, the adjustment of the thermostat set point reduced the heating load by 22.9% at 20 °C, 41.1% at 18 °C, 57.9% at 16 °C, which is in line with Hoyt *et al*. [5], i.e. 10% per °C set point adjustment. The thermal chair plot included the energy consumption of the thermal chairs in Ground Floor which was 8.5% of the week heating load at 20 °C set point, 11% at 18 °C set point and 15.5% at 16 °C set point. Clearly, reducing the set point to 16 °C would result in significant energy reduction but higher thermal discomfort, however, the thermal chair output can be further adjusted to desired levels. Figure 19 compares the hourly heating energy demand for the open plan office (Ground Floor) with thermal chair and non-heated. A similar trend can be observed between the two plots with the heating energy demand generally peaking during the start of the occupancy period. Average of 8.8 kW reduction was observed during the occupancy period.

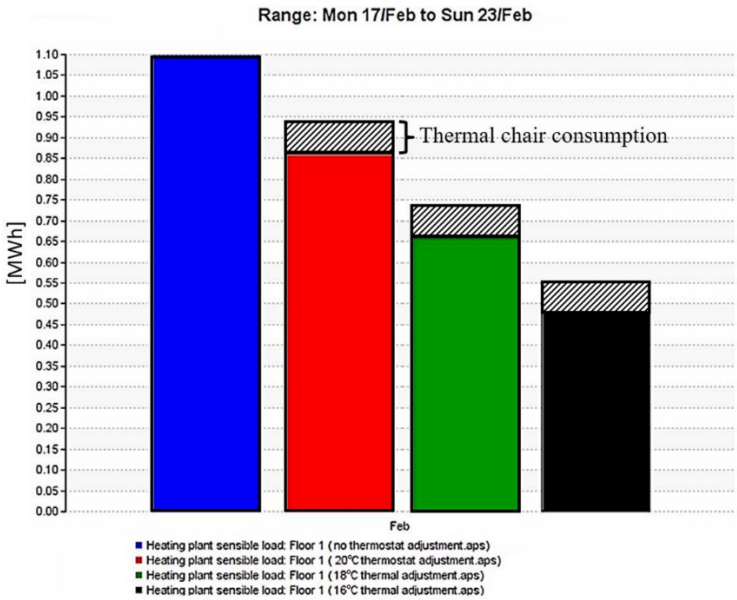

Figure 18. Predicted heat load for the ground floor when the setpoint was adjusted to 20, 18 and 16 °C (17th-23rd February)

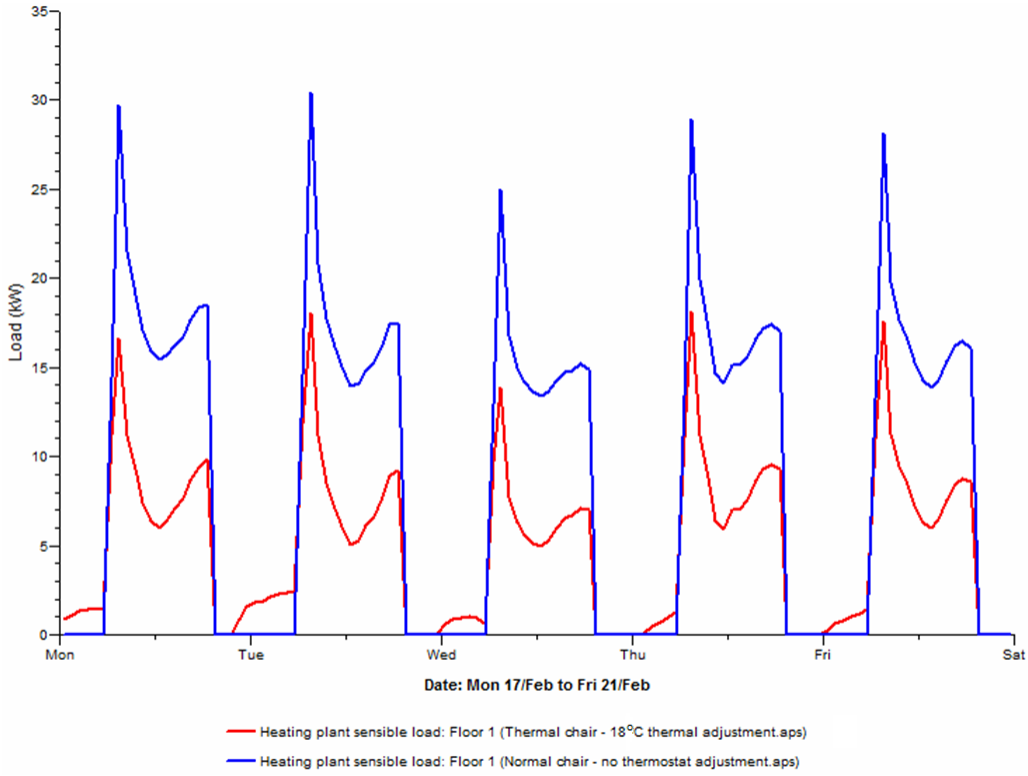

Figure 19. Hourly heating energy demand for the non heated chair and thermal chair with thermostat adjustment (17th-21st February)

CONCLUSIONS

The work presents the analysis of the thermal comfort and energy performance of a thermal chair for open plan office using field tests, survey and simulations. A comprehensive review on the development of thermal chairs was carried out which highlighted the limited studies on the analysis of the energy performance of offices/buildings with thermal chairs. For the field tests, a prototype of a thermal chair was developed by modifying a typical office chair. Two controllable heating pads each with 30 W heat output were incorporated into the back of the seat and back rest fabric.

The study aimed to investigate the subject in an actual office environment in the context of everyday life comparing thermal preference and satisfaction before and after using the thermal chair. The field test was carried out in a modern four storey open plan office building in Leeds, UK during the month of December. During the experiments, the users of the thermal chair were advised to adjust the settings of the thermal chair temperature for the seat and the back rest according to their preference. It was observed that the set temperature ranged between 29-45 °C while several did not use the backrest or seat heating.

The field survey results of the thermal preference showed that 22 out of 44 respondents preferred the thermal environment to be much Warmer/Warmer/Slightly Warmer before using the chair and reduced to 17 after using the thermal chair. While 19 out of 44 respondents preferred no change after using the thermal chair and their thermal sensation varied from Neutral to Hot. The results of the thermal satisfaction survey showed that 19 out of 44 participants felt Satisfied/Very Satisfied before using the device. While after using the thermal chair, the number of Satisfied/Very Satisfied respondents increased to 34. The results highlighted the importance of individual differences in perceiving the thermal environment and its influence on user satisfaction.

The work also utilised BES to further assess the thermal comfort and energy performance of the thermal chair. A three-storey office building with standard and

thermal chairs was generated and simulated in the BES tool IES VE. The results were validated with data from the literature and good agreement was observed between the annual simulation results for heating energy demand (9.7% error) and cooling and energy demand (7.8% error). Unlike previous works, the thermal chair units were integrated into the multi zone building energy simulation model to predict the energy consumption of the building with and without the device. The approach allows for the analysis of the thermal chair together with the building, which typically will have a non-uniform indoor environment. Three cases were simulated, non heated office chair with the zone thermostat maintained at 22 °C, non heated office chair with the zone thermostat at 16-20 °C and thermal chair with the zone thermostat at 16-20 °C. The main aim of the simulations was to predict how much reduction in energy demand can be achieved by adjusting the thermostat set point in the open plan office by during the heating season and what is the effect on the local thermal comfort. Results showed that at 22 °C set point, the PPD was maintained below 5.8% during occupancy hours.

Clearly reducing during the heating period, lowering the set point by a degree few degrees can reduce the energy demand, however, this could also lead to discomfort to occupants. Without any additional heating from the thermal chair, the PMV value decreased from 0 (neutral) to −1.4 (slightly cold) as the set point was decreased from 22 °C to 16 °C. The adjustment of the thermostat set point reduced the heating load by 22.9% at 20 °C, 41.1% at 18 °C, 57.9% at 16 °C, which is in line with previous studies, i.e. 10% per °C set point adjustment. It was observed that the air temperature around the thermal chair was maintained mostly above the setpoint value during the occupied hours. On average the PPD was reduced by 5.6% due to the additional heating from the thermal chair when the set point was at 18 °C and 8.7% at 16 °C. The consumption of the thermal chair was relatively low. It was around 8.5% of the week heating load at 20 °C set point, 11% at 18 °C set point and 15.5% at 16 °C set point.

This study recommends improvement in the BES modelling particularly with regards to the modelling of the thermal chair units. In addition, validation of the integrated model with experiments should be carried out. This study also recommends the further experimental investigation of the thermal chair performance during different periods of the day and year. In addition, future studies can also consider the influence of the use of the thermal chair on the productivity of user. Techno economic analysis and life cycle assessment of the thermal chair should be carried out before the system is put to commercial application.

ACKNOWLEDGMENT

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